

Article

Evaluation of the Improvement Effect of Limestone Powder Waste in the Stabilization of Swelling Clayey Soil

José Luis Pastor , Roberto Tomás , Miguel Cano , Adrián Riquelme  and Erick Gutiérrez

Department of Civil Engineering, University of Alicante (Spain), 03690 San Vicente del Raspeig, Spain; roberto.tomas@ua.es (R.T.); miguel.cano@ua.es (M.C.); ariquelme@ua.es (A.R.); egv.mkz@gmail.com (E.G.)

* Correspondence: joseluis.pastor@ua.es; Tel.: +34-965-90-3400 (ext. 1167)

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Abstract: The natural stone industry generates large amounts of industrial waste every year. Limestone powder produced by the activity of this industry is dumped into landfills, generating an environmental impact that could be reduced by using this waste as a binder in building materials. In the present work, the use of this by-product as an addition for soil improvement of clayey soils has been studied. The tested natural soil is a soft clay from southeastern Spain, which has been mixed by adding 5, 10, 15, 20, and 25% of dry limestone dust by total dry weight of the soil. The natural soil and the additive have been characterized, in addition to the common geotechnical tests, by means of X-Ray diffraction and X-Ray Fluorescence. The improvement of the geotechnical properties of the mixed soil has been evaluated by means of the change in the Atterberg limits, free swell index, unconfined compressive strength, and one-dimensional consolidation test. The change in the microstructure of the mixed soil has been studied by scanning electron microscopy. In general, the results obtained show an increase in the strength of the soil and a reduction of its deformability when limestone powder is added.

Keywords: clay; limestone waste; soil improvement; strength; deformation

1. Introduction

Soil improvement technique has been widely used to reduce soil deformability and increase the shear strength of soft soils. The most common binders used to stabilize soils are cement and lime, or a mixture of both. Nevertheless, these binders have high CO₂ emissions and use vast amounts of raw material during their manufacturing process [1]. In this sense, the use of industrial by-products has two positive environmental effects. On the one hand, it avoids the use of traditional binders, such as cement or lime, which have a negative environmental effect. On the other, it avoids dumping of the waste in a landfill, which presents a strong environmental impact.

In recent years, some research has been done to study the effect of using alternative binders for soil improvement. In this sense, ground granulated blast furnace slag has become one of the most used binders for this purpose, having shown very good effects, such as reduction of swelling potential [2,3] and an increase of the shear strength of soils [3–5]. Similar positive effects have been proven when fly ash is used in clays [6,7]. Kolay and Ramesh [8] found a reduction of the Atterberg limits and swelling when fly ash was added to clayey soils. Horpibulsuk et al. [9] also reported a strength increase of clayey soils when using fly ash as a binder [10], with similar results to those obtained by other researchers [11–13]. The type of available industrial waste depends on the kind of industrial activity in an area or country. Therefore, new binders are being tested to know the effect of its addition to different soils. For example, rice husk ash is one of these new binders that are being used. The general

effect of this ash consists of an increase in the unconfined compressive strength and a decrease in the swelling pressure [6,14,15]. Also, bagasse ash is being studied as a potential addition to expansive soils. Hasan et al. [16] found that this additive has a modest effect on soil strength but significantly reduces the shrink-swell capacity of expansive clays.

Spain is the 7th largest stone producer in the world, having a natural stone production of 3.49 Mt in 2015 [17]. The natural stone industry is one of the most important economic activities in southeast Spain. Consequently, a huge amount of industrial waste is produced every year by this activity. This is not a concern only for Spain; for example, up to 345,000 tons of natural stone sludge is produced per year at the European-wide level [18]. Much of this waste is landfilled, resulting in an environmental impact. Figure 1 shows a series of unplanned landfills in Alicante province (SE, Spain) with a clear impact on the landscape.



Figure 1. View of natural stone waste landfills (LW) in Alicante province (Spain).

Efforts are being made to find any use for this waste which avoids putting it into landfills. Since this is a global problem, some research has been done lately in different countries to use the marble waste powder as a mix with different materials. One of the principal uses has been as a partial replacement of cement for mortar and concrete [19–22]. Some work has also been done to investigate the potential of the marble dust for being used as a binder for soil improvement. Although there is still much research to be done to better understand the effects of marble dust powder for this purpose, some promising results have been produced by former works. Sivrikaya et al. [23] reported a reduction of the Atterberg limits and an increase in the maximum dry unit weight when marble and granite powder from stone plants were added to artificial clayey soils. Saygili [24] found a reduction in the free swell index and an increase in the unconfined compressive strength and in the internal friction angle when marble dust was added to a clayey soil. Similar results were obtained by Sabat et al. [25], who reported an increase in the strength of the soil by means of unconfined compressive strength and the California Bearing Ratio tests. This raise was recorded for marble dust addition up to 20% by dry weight of soil. When this percentage was increased, a reduction of the strength was reported. However, the swelling pressure decreased when marble dust was added up to a maximum percentage used of 25% of marble dust. The same behavior of the expansive index was observed by Ali et al. [26]. Sol-Sánchez et al. [27] found that dolomitic lime from residual sludge was effective as a stabilizing addition to clayey and marly soils due to the increase in pH values, carbonate content, and particle size distribution of the mixed soil when this binder was added. Sivrikaya et al. [23] reported a decrease in Atterberg limits and an increase in the maximum dry unit weight of the compacted mixed soil when marble waste powder was added to an artificial clayey soil. Also, an increase in the strength properties of the mixed soil was found by Brooks et al. [28] when limestone dust was added, although

this increase was not as high as reported in other works for marble dust. Ogila [29] found a reduction in the swelling characteristics of high expansive soil when the limestone dust was mixed with the soil. Sabat and Muni [30] also reported an increase in the strength properties of clayey soils when limestone dust was added. Moreover, a decrease in the liquid limit and the plasticity index and an increase in the plastic limit was found. Nevertheless, according to Brooks et al. [28], there are a limited number of studies about the possible utilization of limestone powder in construction.

Other researchers have studied the stabilization of effluent-contaminated cohesive soils using industrial by-products, such as marble dust and ground granulated blast furnace slag [31], although in this case, the industrial leachate prevents the addition from having the expected positive results.

In this work, the effect of adding limestone powder waste to a clayey soil was studied. The soil used for this work is a natural soil obtained from a trench in a construction site, instead of a clay made with the combination of different clay mixtures, which is more common in the literature. The present work broadens the knowledge of the effect of this by-product as a binder on the compressive strength, microstructure, and swelling potential of the mixed soil, which has hardly been studied. Moreover, in this work, the deformability of the soil with the additive has been studied. The soil is going to be used as an embankment in a real project, where the water table level is near the ground surface, so the natural water content of the soil is high. The dry mixing method for soil mixing using cement as the binder, where the cement is added directly to the sample, is more efficient when the moisture content of the natural soil is high [32], and it is the common procedure when soft soils are encountered near the surface. Therefore, in this study, the limestone powder is added dry to the soil with the natural water content. Finally, deformability and strength properties of the mixed soil are studied by physical and mechanical tests.

2. Materials and Methods

2.1. Materials

2.1.1. Soil

The soil used in this study was a natural clayey soil from the Almeria province, southern Spain. Table 1 shows the main geotechnical properties of this soil. It is classified as a medium-low plasticity clay (CL) according to the Unified Soil Classification System (USCS) [33]. The mineralogical and chemical characterization of the soil was performed by means of X-Ray Diffraction (XRD) and X-Ray Fluorescence (XRF), respectively. The results obtained in these tests are shown in Figure 2 and Table 1.

Table 1. Main geotechnical properties of the soil used in this study.

Property	Value	Property	Value
% Sand (0.06–2 mm)	15	Plasticity Index	20.8
% Silt (0.002–0.06)	60	Activity	0.83
% Clay (<0.002 mm)	25	Free swelling	5.70 ¹
Liquid Limit	44.6	Particle density (kN/m ³)	26.0
Plastic Limit	23.8	Soil classification (USCS)	CL

¹ For a natural water content of 12%.

The semiquantitative mineralogical analysis performed using XRD shows that tested soil sample consists of illite 28.7%, calcite 22.5%, quartz 19.4%, gypsum 7.6%, montmorillonite 5.9%, and kaolinite 3.9%. According to this analysis, the predominant clay mineral in the soil is illite, which is consistent with the activity of the soil shown in Table 1. Normal clays usually present an activity between 0.75 to 1.25, with 0.90 being a common value for illite minerals [34]. A medium to high swelling potential, such as that obtained in the free swelling test, is expected for a soil with the geotechnical properties, percentage of clay, and activity shown in Table 1 [35].

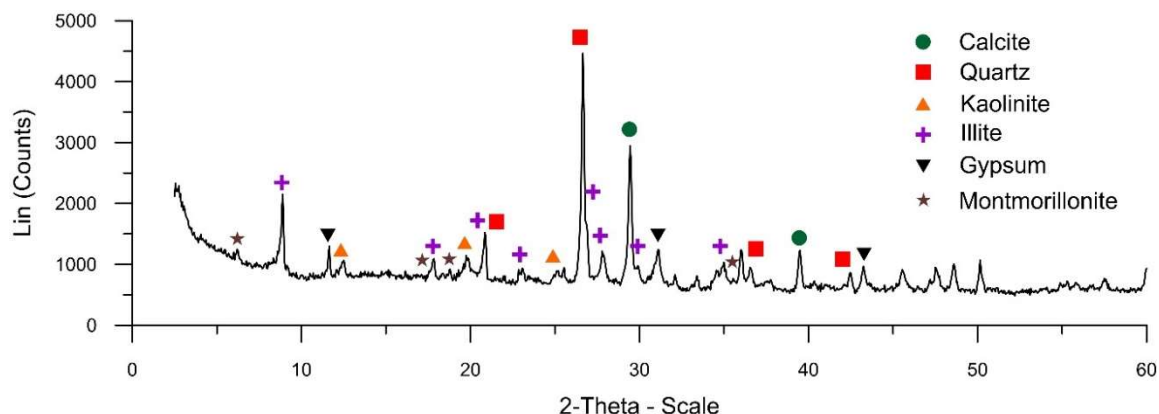


Figure 2. XRD results for the clayey soil.

2.1.2. Additive

The additive used in this research was limestone powder waste, obtained from a dumpsite of a natural stone industry from cutting and polishing works. This additive is mainly composed of carbonates (CaCO_3 and $\text{CaMg}(\text{CO}_3)_2$). The results of the DRX and FRX analysis are shown in Figure 3 and Table 2, respectively. The mineral composition of the limestone powder obtained by a quantitative analysis of the DRX results is calcite 67.8% and dolomite 26.1%. In this study, the additive is expected to work as a filling material because the effects of the addition are studied only in the short term. Nevertheless, the calcium carbonate composition of the additive could generate pozzolanic reactions between the calcium ions and the silica and alumina of the clay minerals in the long term. These reactions can bring the formation of cementitious products, such as calcium-silicate-hydrates (C-S-H), calcium-aluminate-hydrates (C-A-H), and calcium-aluminium-silicate-hydrates (C-A-S-H) [24]. Previous works reported the formation of cementing and poorly crystalline gels when calcium carbonate with lime was added to clays [36].

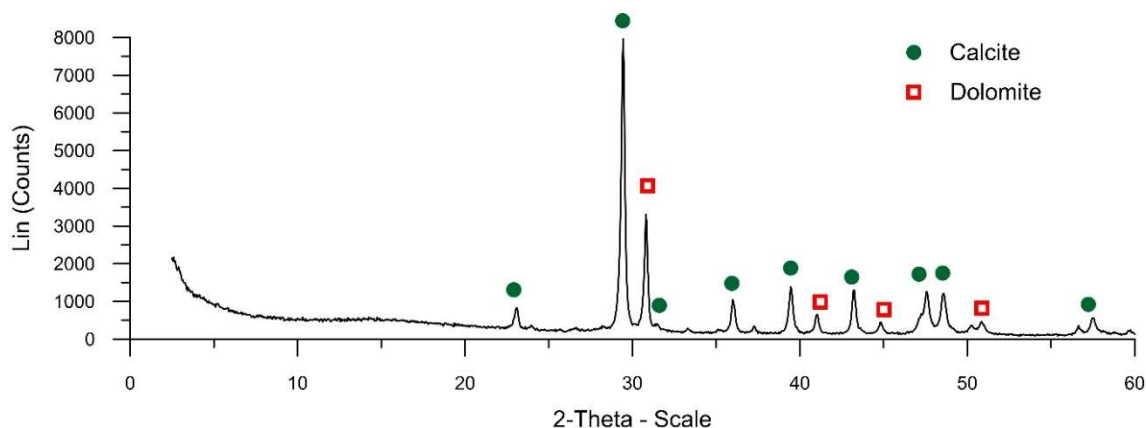


Figure 3. XRD results for the additive.

2.1.3. Mixed Soil

As this research intends to simulate the real mixing of the soil and the additive in the field, the natural moisture content of the soil was used to prepare the samples. The soil was dried in an oven at 40 °C to a constant weight; afterwards, the material was disaggregated and passed through a 0.40 mm sieve. Subsequently, 31% of water by total dry weight of the soil was added, obtaining a homogeneous soil with the same moisture content as in the field. Finally, samples were prepared by adding 5, 10, 15, 20, and 25% of dry limestone dust by total dry weight of the soil. The samples were prepared after mixing the additive and stored in a curing room at a controlled temperature of 20 ± 2 °C and 95% of relative humidity for 7 days, after which they were tested. Every test was

performed in triplicate per each dosage, except for the unconfined compressive strength test of the natural soil, which was performed over five samples.

Table 2. The chemical composition of the soil and the additive determined by FRX analysis.

Compound	Soil Mass %	Additive Mass %
Na ₂ O	0.919	0.183
MgO	5.290	5.085
Al ₂ O ₃	13.902	0.571
SiO ₂	36.669	1.353
P ₂ O ₅	0.316	0.139
SO ₃	2.760	0.273
Cl	0.248	0.101
K ₂ O	2.907	0.105
CaO	14.722	62.658
TiO ₂	0.644	0.036
Cr ₂ O ₃	0.018	0.258
MnO	0.070	0.034
Fe ₂ O ₃	5.461	0.041
SrO	0.175	–

2.2. Methods

2.2.1. X-Ray Diffraction

The soil and the additive were characterized by XRD using a Bruker D8-Advance X-Ray diffractometer (Bruker, Billerica, MA, USA), with a high-temperature Chamber (up to 900°C), with a generator of x-ray KRISTALLOFLEX K 760-80F (Bruker, Billerica, MA, USA, power: 3000W, voltage: 20–60KV and current: 5–80mA) with a tube of RX with a copper anode.

2.2.2. X-Ray Fluorescence

The soil and the additive were characterized by an X-ray sequential spectrometer PHILIPS MAGIX PRO (Philips, Amsterdam, Netherlands) equipped with a rhodium X-ray tube and beryllium window. PW2400 spectrometer (Philips, Amsterdam, Netherlands) is a sequential instrument with a single goniometer based measuring channel, covering the complete measuring range.

2.2.3. Atterberg Limits

The Atterberg limits of the soil were determined using the Spanish standards UNE 103103 [37] for the Liquid Limit and the UNE 103104 [38] for the Plastic Limit, corresponding both standards to ASTM D 4318 [39].

2.2.4. Free Swell Index

The tests for the assessment of the free swelling of the soil in the oedometer device were conducted according to the UNE 103601 [40] and the ASTM D4546 [41]. The samples for the swelling tests were prepared by adding 12% of water to the dry natural soil to better understand the effect of the additive on the swelling potential. This water content corresponds to the lowest interval value of the optimum moisture content for compacting clays according to Carter and Bentley [42], which allows observation of the swelling potential of the soil. Afterwards, samples were prepared by adding 5, 10, 15, 20 and 25% of dry limestone dust by total dry weight of the soil. All the samples were compacted with an energy source corresponding to the Standard Proctor compaction energy. Each sample had a diameter of 50 mm and an initial height of 20 mm. Eighteen free swelling tests were performed—three tests per each dosage and three for the natural soil.

2.2.5. Unconfined Compressive Strength

The Unconfined Compressive Strength (UCS) of the natural and mixed soil were determined according to the standards UNE 103400 [43] and ASTM D2166 [44]. The unconfined compressive strength is equal to the maximum value of compressive stress or the compressive stress at 15% axial strain, whichever is secured first. All the samples were compacted with an energy corresponding to the Standard Proctor compaction energy. Each sample had a diameter of 50 mm and an initial height of 100 mm. The loading rate was 1 mm/minute, being the UCS maximum strength value obtained from the start of the test up to a deformation equal to 15% of initial vertical height. Three tests per dosage and five for the natural soil were performed, making a total of 20 unconfined compressive tests.

2.2.6. One-dimensional Consolidation

The 1-D consolidation tests were performed according to the Spanish Standard UNE 103405 [45] for 0, 5, 10, 15, 20, and 25% of limestone waste powder addition. All the samples were compacted with an energy corresponding to the Standard Proctor compaction energy. Tests were conducted under the loading path of 5, 10, 20, 50, 100, 200, 400, and 800 kPa and an unloading path of 400, 200, 100, 50, and 20 kPa. Each sample had a diameter of 50 mm and an initial height of 20 mm. A total of 18 1-D consolidation tests were performed—3 tests per each dosage and 3 for the natural soil.

2.2.7. Scanning Electron Microscopy (SEM)

The structure of the natural soil and the soil with 20% of limestone powder were examined using a JEOL JSM-840 Scanning Electron Microscope (SEM Tech Solutions, Billerica, MA, USA). The accelerating voltages used for this work were set between 10 and 15 kV. The samples were made conductive by coating them with gold.

3. Results

3.1. Atterberg Limits

The results of the Atterberg limits are shown in Figure 4. As can be seen in this figure, a clear decrease is observed in Liquid Limit (LL) and Plasticity Index (PI) when limestone powder is added. LL and PI values decrease from 44.6 and 20.8 to 37.2 and 14.1, respectively. This decrease corresponds to a reduction of 17% for the LL and of 32% for PI when the additive is added. The addition of this binder seems to have little influence on the value of the Plastic Limit (PL), remaining approximately constant for the natural soil and the mixed soil.

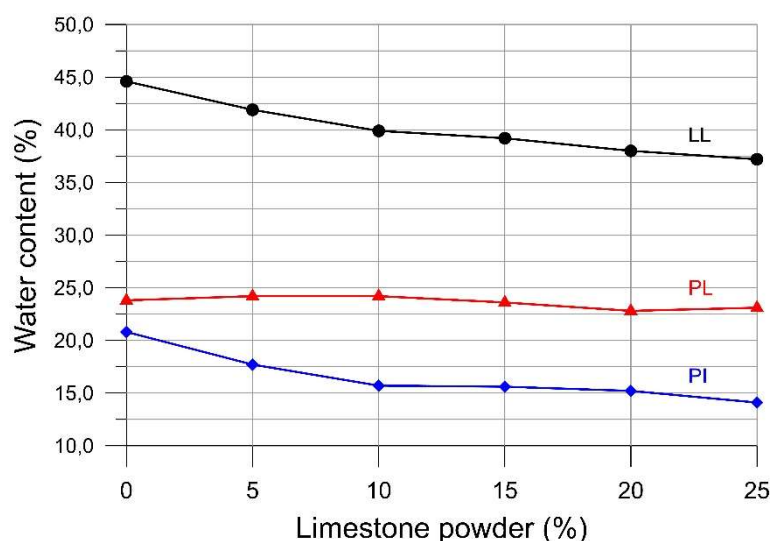


Figure 4. Effect of limestone powder content on the Atterberg limits of stabilized clay.

3.2. Free swell index

The results of the percentage of free swell for samples prepared by adding from 0 to 25% of limestone powder are depicted in Figure 5. Free swelling is reduced from 5.70% for natural soil to 3.33% when only 5% of limestone powder is added. For additions higher than 5%, less reduction is achieved, obtaining values of 2.39, 2.22, and 2.49% of free swelling for 10, 15, and 20% of limestone powder, respectively. On the contrary, an increase up to 3.90% is observed for mixed soil with 25% dust.

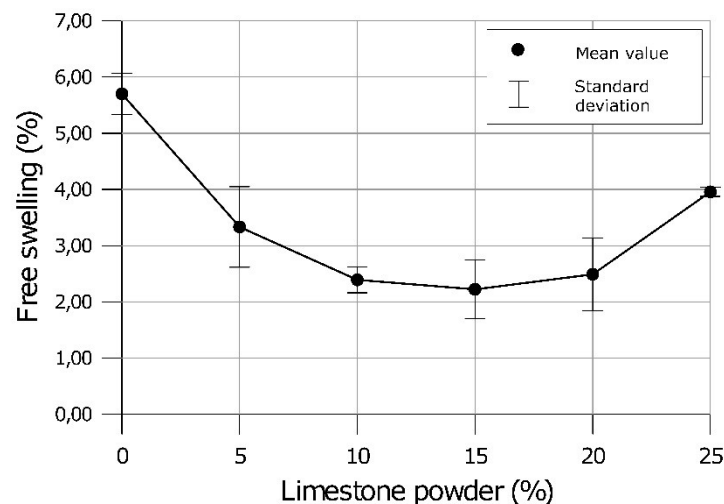


Figure 5. Effect of limestone powder content on the free swell index of the stabilized clay.

3.3. Unconfined Compressive Strength

Axial strain versus axial stress relation for all the tested samples is shown in Figure 6a. The natural soil samples present a typical parabolic shape with a small deviation in the five tested samples. This stress-strain behavior changes from the parabolic to a bilinear shape when limestone powder is added. In these bilinear curves, the initial slope is similar for all the samples, regardless of the amount of addition. Nevertheless, the second slope of the curve increases as the amount of limestone powder increases. All the samples, with and without addition, present a ductile behavior without defined peak stress. Due to this ductile behavior, the UCS is obtained as the axial stress when the axial strain is equal to 15%.

The results of the UCS for samples prepared by adding from 0 to 25% limestone powder are depicted in Figure 6b. As can be seen in this figure, the UCS increases as the amount of limestone powder increases. Nevertheless, the rate of increase is much higher from 0 to 20% of addition than from 20 to 25%, where the line is nearly horizontal. The effect of limestone powder content on the E50 soil modulus and strain at 50% of the maximum stress is also shown in Figure 6b. An upward general trend can be seen in the E50 modulus as the limestone dust increases from 0 to 20%. Nevertheless, the E50 modulus decreases from 20 to 25% of addition. It is worth noting that the upward general trend from 0 to 25% is more evident if the outlier, which presents a high value of E50 for 5% of addition, is deleted.

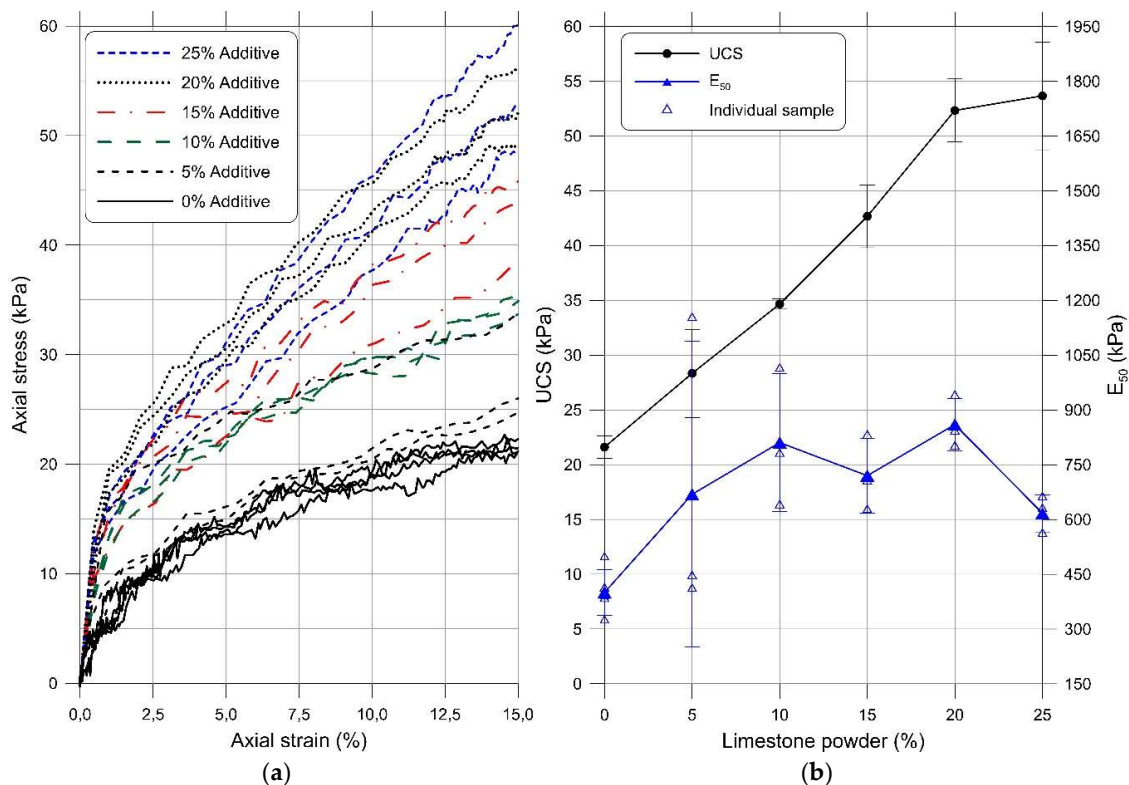


Figure 6. Effect of limestone powder content on the Unconfined Compressive Strength (UCS) of stabilized clay. (a) Axial strain vs. axial stress; (b) limestone powder content vs. UCS and E_{50} .

3.4. One-dimensional consolidation

The normalized void ratio versus log stress relationship for the three samples of natural soil and the mixed soil is shown in Figure 7. As can be seen in this figure, a general trend of reducing the normalized void ratio for the last steps of the loading path (800 kPa) is observed as the amount of limestone powder increases. Two 1-D consolidation curves, one for the natural soil and the other for 20% additive, show anomalous values in two steps of the loading path (Figure 7). Therefore, these two curves were not taken into consideration in the calculation of the Compression (C_c) and the Swelling (C_s) indexes. C_c expresses the relative compressibility of the soil and is determined from the straight portion of the loading path of the void ratio versus log stress relationship. C_s was obtained from the slope of the unloading straight portion of the same curves. The effect of limestone powder content on the C_c and C_s of the stabilized clay is depicted in Figure 8. The general trend observed in Figure 7 is more evident in Figure 8, as C_c , and also C_s , decreases from 0 to 25% of additive content.

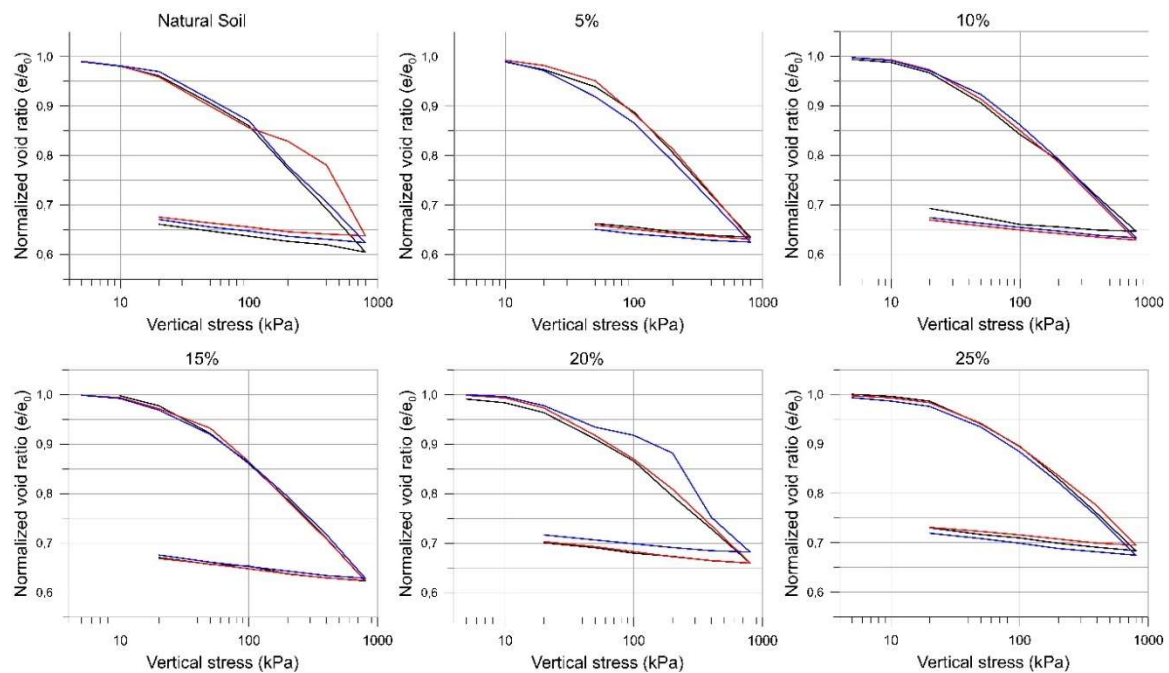


Figure 7. Normalized void ratio versus log stress relationship for the natural soil, 5, 10, 15, 20, and 25% of limestone powder content.

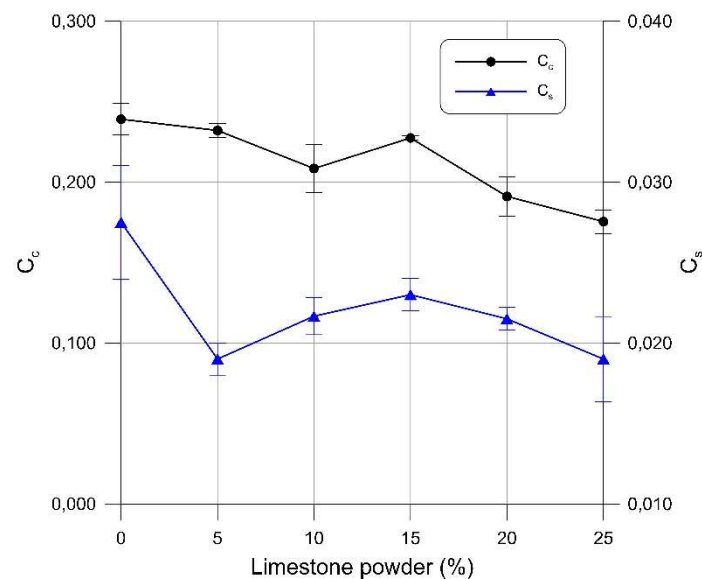


Figure 8. Effect of limestone powder content on the Compression index (C_c) and the Swelling index (C_s) of the stabilized clay.

3.5. Scanning Electron Microscopy

The microstructures of the natural soil and the soil with 20% of limestone powder are shown in Figures 9a and 9b, respectively. The microtexture of the natural soil is significantly modified by the addition of the limestone powder. The untreated natural soil presents a less compact structure than that observed in the treated soil. Clean clay particles are observed in the SEM image of the natural soil, whilst the image of the soil with the additive shows these particles covered and pore spaces filled by fine aggregates.

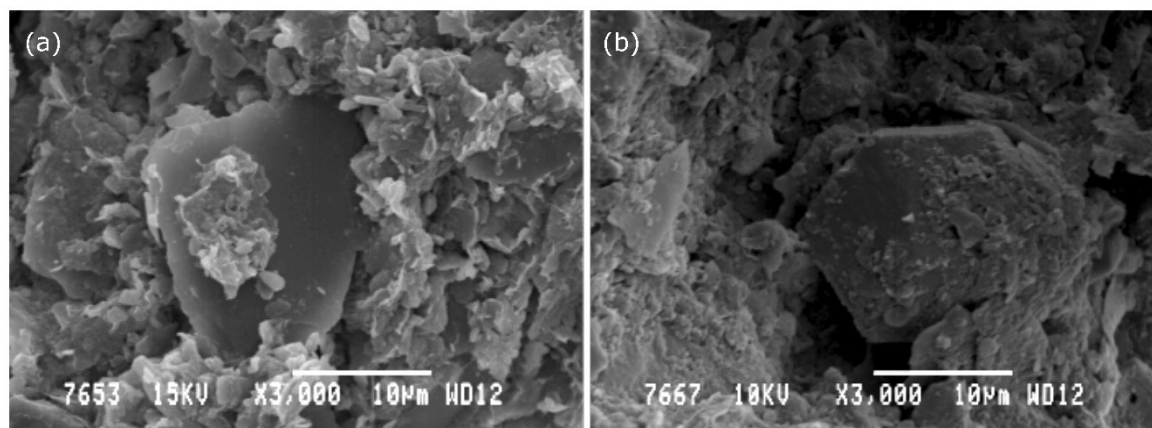


Figure 9. SEM images of (a) natural soil, and (b) natural soil with 20% of limestone powder addition after 7 days of curing.

4. Discussion

The results obtained show a general positive effect of the addition of limestone powder to clayey soils.

Although the Atterberg limits of the soil do not show a big change when the waste is added, the Liquid Limit and the Plasticity Index present a clear decrease with the addition of the dust. Similar results were found by Sabat and Muni [30] when adding limestone dust to an expansive clay, for Sirvrikaya et al. [23] for marble dust addition, and for Igwe et al. [46] when granite and dolerite dust was added to a clayey soil. Nevertheless, the reduction obtained in this work was a little higher.

Regarding the effect of the limestone powder addition on the free swelling of the soil, a general trend is observed of reduction of the index when this industrial by-product is added. Free swelling is reduced from 5.70% for natural soil to 3.33% when only 5% of limestone powder is added. This constitutes a reduction of 42% in the free swelling of the mixed soil. As stated above, smaller relative reductions of the free swelling are achieved when the amount of additive is increased. A reduction of 58, 61, and 56% are observed when the limestone powder addition is of 10, 15, and 20%, respectively. Only a reduction of 31% is obtained for 25% of limestone powder, breaking the downward trend observed from 0 to 20%. A decrease in the swelling index up to the maximum amount of marble dust addition was found by previous research [24,26], although Ali et al. [26] only studied a maximum addition of 12%. Ogila [29] reported a decrease between 30 to 45% of the heave percentage when 20% of limestone dust was added to three different clayey soils, similar to results obtained by Sabat and Muni [30], although in that case the maximum limestone powder added was 12%. The increase of the swelling index for 25% of limestone powder is probably due to the considerable increase of matric suction caused by the reduction of the initial water content of the samples, since the dust is added dry to the wet soil.

The Unconfined Compressive Strength of the mixed soil increases with the amount of limestone powder, obtaining an increase of 31, 60, 98, 142, and 148% when 5, 10, 15, 20, and 25% of waste is added, respectively. These results show a clear improvement of the compressive strength of the soil with the addition of this by-product. According to Ni et al. [47], the contribution of fines to the compressive strength of mixed soils depends on the relative hardness between the fines and the coarser grains. If fines are harder than the coarser grains, their presence can have a positive contribution in the compressive strength of the soil. Although the soil studied in the present research is not a mixed soil, in addition to the binder effect of the limestone dust, a similar effect to the one described by Ni et al. [47] can occur. As stated in Section 2.1.1, the natural soil consists mainly of illite, calcite, quartz, gypsum, montmorillonite, and kaolinite (Figure 2). All these minerals, except for quartz and calcite, present a hardness in Mohs scale lower than the fines provided by the additive that fill the voids (Figure 9), mostly composed of calcite and dolomite (Figure 3). Therefore, the added fines have a

higher hardness than most of the particles presented in the natural soil and could be responsible for the observed increase of compressive strength of the soil.

The UCS rate of increase is much higher from 0 to 20% of addition than that observed from 20 to 25%. This could mean that there is a threshold in the beneficial effect of the addition at around 20%. Similar results were obtained by Saygili [24] and Sabat et al. [25], although in this last study the UCS and the California Bearing Ratio (CBR) show a maximum value for 20% of marble dust and a decrease for 25 and 30% of this addition. Sabat and Muni [30] also found a threshold value when adding limestone dust to an expansive soil, although in this case it was found for 9% of addition. The stress-strain behavior when the limestone powder is added shows a progressive change from a parabolic curve to a bilinear one. This bilinear behavior is more pronounced as the amount of addition is higher. The slope of the second part of the curve also increases as the amount of limestone powder increases. This behavior could be due to the addition of a non-cohesive material to the clayey soil. For this reason, as the amount of limestone waste increases, the mixed soil stress-strain behavior moves away from the common behavior of soft soils.

The E_{50} soil modulus also shows an upward general trend from 0 to 20%, being increased by 67, 103, 80, and 115% when 5, 10, 15, and 20% of dust is added, respectively. As said above, this trend is more evident if the two anomalous values, which present high values of E_{50} , are deleted, one for 5 and another for 10%. In this case, the increase was 7, 77, 80, and 115%. A reduction of the E_{50} is observed from 20 to 25% of limestone dust. According to these results, the soil tends to not only increase its compressive strength but also its stiffness when limestone powder is added. This is in line with the general trends found in previous works [48,49], where an increase in the E_{50} modulus was observed when the UCS increased. According to Ayeldeen et al. [50], E_{50} can be estimated for disturbed cement-stabilized soft clay as between 25 to 50 times UCS. Other authors increase this value to between 50 to 150 times [51]. Nevertheless, the ratio obtained in the present study is a little smaller, with $E_{50} = 17$ UCS ($R^2=0.88$) when considering the results from 0 to 20% of addition, and $E_{50} = 16$ UCS ($R^2=0.47$) when considering the results from 0 to 25%. The anomalous results of E_{50} have not been taken into account in either of these values.

Ayeldeen et al. [50] reported that undisturbed cement-stabilized clay, with higher ratios E_{50}/UCS , up to 160, shown brittle behavior with a clear peak. Nevertheless, re-molded samples with lower ratios have shown a ductile strain-stress behavior without a clear peak. Similar behavior has been observed in the present research. When limestone powder is added to the clayey soil, small ratios E_{50}/UCS are reported, with a ductile behavior being observed.

The increase in the stiffness of the soil when limestone powder is added is confirmed by the decrease of the soil compressibility when it is tested in the oedometer apparatus. The compression index, which is a direct indication of the tendency of a clayey soil to settle when it is loaded, decreases as the amount of additive increases. The C_c index is reduced by 3, 13, 5, 20, and 27% when 5, 10, 15, 20, and 25% of dust is added, respectively. A similar trend is observed for C_s index as the amount of limestone powder increases, with a maximum reduction of 31% when 25% of powder is added. Therefore, this addition decreases the compressibility of the soil as the slope of the virgin and rebound consolidation curves are reduced. This lower compressibility of the mixed soil is attributed to the fine aggregates of the limestone powder dust filling the voids of the natural soil. The SEM images shown in Figure 9 support this idea, as the treated soil presents a more compact structure than that observed in the natural soil.

5. Conclusions

The effect of the addition of limestone powder to a clayey soil on Atterberg limits, free swelling index, unconfined compressive strength, compressibility, and microstructure has been studied. Experimental results show a moderately beneficial effect on the geotechnical properties of the clayey soil when limestone powder is added that can be summarized as follows:

- There is a reduction of the Liquid Limit and Plasticity Index up to 17 and 32%, respectively, when 25% of the additive is added.
- The reduction of the free swelling index reaches a maximum value of 61% when 15% of powder is added.
- The unconfined compressive strength increases up to 148% for the maximum percentage of addition.
- A reduction of the compressibility of the mixed soil is observed. C_c and C_s indexes decreases up to 27% and 31%, respectively, when the soil is mixed with 25% of limestone powder.
- SEM images show a more compact microstructure of the soil when the limestone powder is added.

Although the addition of limestone powder to clayey soils achieves a moderate improvement on the geotechnical properties of clayey soils, the use of this addition has a very positive environmental effect, both by avoiding the use of traditional binders, which have a strong environmental effect on its manufacturing process, and by avoiding dumping the waste from the natural stone industry into landfills. It is noteworthy that the environmental benefits of the use of limestone powder, as of any other binder, will depend on the distance between the quarries, or the storage, and the work.

In conclusion, this research highlights the potential re-evaluation of limestone powder waste as a binder material for the improvement of clayey soils, enabling reduction of the negative impacts of this waste and obtaining economic and environmental benefits from its reuse.

Author Contributions: J.L.P., R.T. and M.C. designed the methodology of the research. J.L.P. and E.G. performed the experiments. R.T. and M.C. supervised the investigation. J.L.P. wrote the paper. R.T., M.C. and A.R. reviewed and edited the manuscript.

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